I. Introduction

The CRBRP Project was established with the principal objectives of demonstrating that an LMFBR can operate reliably and safely in a utility environment, demonstrating fast breeder reactor technology and serving as a successful transition from R&D efforts to large-scale commercial LMFBR plants.

The LMFBR has long been recognized as the most viable alternative reactor type to the LWR and the uranium fuel cycle. The U.S. and other industrial countries have made extensive national commitments toward developing LMFBRs which include the successful operation of several liquid metal test and power reactors.

II. Design

A. Major Design Objectives

The unique design objective of LMFBRs is to breed fuel. A parameter defined to quantify the efficiency of this design objective is the "breeding ratio." The breeding ratio is defined as the amount of fissile material produced divided by the amount of fissile material consumed in a specified operating period. Commercial LWRs are called thermal converter reactors since this ratio is less than one. LMFBRs are designed to have breeding ratios greater than one.

In order to attain a high breeding ratio, the neutron flux of a LMFBR must be a "fast flux" (>100 Kev) rather than a "thermal flux" as is present in LWRS (0.025 ev at room temperature).

This is primarily due to the large reduction in capture to fission ratio in Pu^{239} with increasing energy. Due to the relatively small fission cross-sections of fissile nuclei at higher energies, the fuel of a LMFBR must have a higher enrichment than a LWR to become critical. To ensure that the high energy neutrons utilized in a fast breeder reactor are not slowed down or absorbed, a coolant with a low absorption and scattering cross-section is required. This is in direct contrast to a LWR where a good moderator is essential.

B. Reactor Design

The differences in the LWR and LMFBR reactor core designs are due primarily to the requirement on the LMFBR to breed fuel. LMFBR reactor cores contain regions of fertile material (depleted U-238) commonly referred to as "blanket regions" or "blanket assemblies" where the majority of breeding occurs. A core arrangement in which the fertile blanket region remains entirely outside of the active core region (where an initial loading of fissile fuel is located) is termed, "homogeneous." This term is used because of the relatively uniform or homogeneous distribution of fissile fuel in the active core region. A core arrangement that includes fertile blanket assemblies within as well as around the active core region is termed "heterogeneous." Heterogeneous core designs are desirable because of their higher breeding ratios and their reduced positive sodium void coefficients of reactivity. Figure 1 illustrates a typical homogeneous and heterogeneous core arrangement. Early U.S. prototype LMFBRs and all foreign LMFBRs use the homogeneous core design. Demonstration of the heterogeneous core design in the Clinch River Breeder Reactor is expected to provide a significant advance in LMFBR technology. Radial shield assemblies are provided around the periphery core to reduce the neutron fluence experienced by the reactor vessel and surrounding structures.

The size of a LMFBR core is not influenced by the need to optimize the fuel to moderator ratio as in a LWR. Instead, a very "tight" design is desired to offset the relatively low fission cross section for high energy neutrons. Thus, the volume fraction of coolant and structural materials in an LMFBR core is reduced relative to a LWR. The high fuel enrichment and high thermal conductivity of the coolant makes it desirable and possible to design a core with a power density much higher than that of a LWR. As a result of this, a LMFBR core is smaller than a LWR core of the same thermal power. To maximize the fuel volume fraction a triangular fuel lattice and hexagonal assembly structure is utilized in an LMFBR in place of the rectangular lattice and assemblies used in LWRs.

Figure 2 is a simplified schematic of a typical LMFBR fuel assembly. There are 217 fuel rods in each CRBRP fuel assembly, spaced in a triangular array by spiral wire wraps. Each rod contains a 36-inch-long stack of fuel pellets and two 14-inch-long stacks of blanket pellets (located above and below the fuel pellets). Blanket assemblies are similar, but contain larger pins; 61 per assembly; loaded entirely with depleted uranium oxide pellets. (See Figure 3).

C. Heat Transport System

LMFBRs require a coolant with low absorption cross-section, low neutron thermalization characteristics and high heat transfer coefficients. Sodium has been generally chosen as the coolant for fast breeder reactors because of its relatively low cost, availability, acceptable nuclear properties and excellent heat transfer properties. One of the most important properties of sodium is high thermal conductivity: approximately 30 Btu/hr-ft-$^{\circ}$F vs. 0.3 Btu/hr-ft-$^{\circ}$F for water.

Furthermore, sodium has a boiling point of about 1620°F ($\sim$880°C) at atmospheric pressure. This allows LMFBRs to operate at essentially atmospheric pressure since coolant operating temperatures are typically on the order of 600-700°F below the boiling point.[1] This is in contrast to LWRs which operate at pressure around 1050 psia for BWRs and 2100 psia for PWRs.

The exit (1000°F) temperature of sodium leaving the reactor in an LMFBR is considerably higher than that of a LWR (600°F). The temperature differential between the hot and cold leg of an LMFBR (300°F) is larger than for a LWR (100°F).

All nuclear reactor designs must include heat transport systems which are capable of providing a heat sink during operation in addition to removing the decay heat produced in the reactor following shutdown. BWRs utilize a direct cycle where heat is transferred directly from the reactor core to the turbine generator. PWRs on the other hand utilize an indirect cycle where the heat produced in the reactor core is transferred to the steam generators in order to generate steam for driving the turbine generator.

LMFBR heat transport systems consist of a primary sodium system, an intermediate sodium system, and a feedwater/steam system. The intermediate sodium system, unique to LMFBR, is used to provide an additional barrier between the radioactive primary sodium and the water in the steam generators. The intermediate heat exhanger (IHX), between the primary and intermediate sodium coolant, is unique to LMFBRs. The radioactive primary coolant system is enclosed within inerted primary equipment cells inside containment. Only the intermediate (non-radioactive sodium) is circulated outside containment to the steam generators. This design approach affords protection of plant personnel from the primary sodium radiation during operation and also functions to mitigate accidental sodium leakage from the primary system.

[1] Normal full power operating pressures of about 170 psig are attributed to pump and static head pressures.

The two types of primary heat transport system arrangements that are currently being used in LMFBRs are the pool and loop system. In the pool system the reactor, intermediate heat exhangers and primary sodium pumps are all located in a tank full of sodium. This pool design was first used in the U.S. experimental breeder reactor EBR-II but has since been adopted by France, the United Kingdom, and the Soviet Union. In the loop system the primary coolant is circulated through a piping configuration which extends outside of the reactor vessel to the pumps and intermediate heat exchanger. The loop design is currently being used by Germany, Japan, the United States, and the Soviet Union.

The CRBRP heat transport system, which is a typical loop design, is illustrated in Figure 4. The CRBRP heat transport system features three redundant and physically independent loops for normal and decay heat removal. Both the primary and intermediate heat transport systems are fully welded coolant boundaries. Coolant leakage is essentially zero during normal operation. This contrasts with LWRs which use flanges at some locations in the coolant boundary and accept some coolant leakage.

D. Auxiliary Systems

An LMFBR design includes several auxiliary systems that are not found in LWRs and vice-versa. Auxiliary systems typical of those used in LMFBRs are discussed below.

Refueling operations in LMFBRs are performed without removing the reactor vessel head. Figure 5 shows the reactor refueling arrangement for CRBRP. The CRBRP reactor refueling system utilizes major features of the refueling systems in earlier liquid-metal cooled reactors in the United States - the Fast Flux Test Facility (FFTF), Hallam, Sodium Reactor Experiment, Fermi, and EBR-II reactors - as well as features from the German, French, and British LMFBR programs.

Core assemblies are removed from the reactor under sodium cover by a straight-pull in-vessel transfer machine (IVTM). The IVTM is sealed and mounted within the smallest of three eccentric rotating plugs on the reactor closure head. The IVTM grapple lifts the core assembly above the core. The core plugs are rotated and the core assembly is placed in a core component pot waiting in the reactor vessel, but outside the core region. The ex-vessel transfer machine (EVTM) removes the core component pot filled with sodium and the core assembly from the reactor vessel and transfers it to the ex-vessel storage tank.

The sodium-filled ex-vessel storage tank (EVST) is used for storing spent fuel assemblies. This facility is functionally similar to the LWR fuel storage pool but incorporates features necessary to accommodate sodium.

An auxiliary liquid metal system is utilized in LMFBRs. The auxiliary liquid metal system performs the following functions:

- o Receives liquid metal and transfers it to storage vessels in the plant.
- o Purification (cold trapping) and storage of sodium limiting the oxygen and hydrogen concentration of the sodium.
- o Filling and draining the reactor and EVST coolings systems.

These systems perform functions analagous to LWR water clean up systems. Liquid metals can be uniquely cleaned by using cold traps.

Since the melting point of sodium is about 210^{o}F, electrical trace heaters are provided around the outside of LMFBR piping and components to preheat systems prior to sodium fill. Trace heaters need only operate on the reactor vessel and heat transport system piping when insufficient heat is available from power operation or decay heat to maintain the sodium in a liquid state. Many drain lines and other equipment associated in the auxiliary liquid metal system require continuous operation of the trace heater system when those features are being used. The extent of this system is unique to the LMFBR but is functionally similar to heating water pipes to avoid freezing.

The reactor vessel, guard vessel, and primary heat transport system piping and components of LMFBR designs are usually placed in cells having atmospheres chemically inert to sodium. Nitrogen is most often used as the inert atmosphere for these cells because it is readily available and inexpensive. A small amount of oxygen (approximately 1%) is maintained in cell nitrogen to prevent nitriding. The inert atmosphere significantly reduces fire consequences as the result of a postulated sodium spill. Because pure nitrogen can not be used in steel enclosures at higher temperatures (>750°F) due to nitriding, and even 1% O_2 would not co-exist with liquid sodium, argon has been selected as the cover gas for use within the reactor vessel and all other major HTS piping and components.

An inert gas receiving and processing system is typically included in the LMFBR designs to provide nitrogen to inerted cells and to provide Argon cover gas to all free liquid metal surfaces and to component and reactor head seals. Subsystems are provided for processing contaminated (radioactive) Argon and nitrogen.

III. Safety

A. Fundamental Safety Considerations

A major effort is made to assure LMFBR's, like LWR's, are designed to operate reliably within normal plant parameters so that safety systems are not challenged frequently. However, it is recognized that safety features must be provided and carefully assessed to assure protection of public health and safety for even low likelihood events.

The three fundamental safety considerations for an LMFBR are no different than the safety considerations for a LWR.

First, if any significant off normal event occurs, the reactor must be shutdown in a timely manner to avoid exceeding fuel design limits. The CRBRP Reactor Shutdown System (RSS) consists of two redundant and diverse shutdown systems: the Primary RSS and the Secondary RSS. Each one of these reactor shutdown systems independently brings the reactor to a safe shutdown condition by inserting control rods into the reactor core.

Second, the reactor must be adequately cooled following reactor shutdown. The CRBRP design meets this objective by providing four separate paths for decay heat removal.

Guard vessels that surround major heat transport system components to protect against the potential loss of sodium are features found in most LMFBR designs. The guard vessels are located and sized to accommodate pipe leaks without lowering the sodium level in the reactor vessel below the minimum level required for cooling the reactor vessel core. In the CRBRP design, guard vessels are provided for the reactor vessel, primary pumps, intermediate heat exchangers, and all primary system piping at an elevation below the top of the guard vessels. The guard vessel-elevated piping concept is illustrated in Figure 6. This passive approach to ensuring a sufficient inventory of primary coolant performs a function similar to that of the active Emergency Core Cooling System (ECCS) of a LWR.

The high thermal conductivity of sodium and the substantial margin to boiling allow adequate decay heat to be removed from the core at low flow rates. The sodium expansion through the core and compression through the intermediate heat exchanger (IHX) allows a natural thermal driving head to be established. Figure 7 illustrates how the location of component thermal centers enhances natural circulation. This natural circulation process can adequately remove decay heat from the core even if all other pumping power for the primary sodium is lost.

Third, any significant leakage of radioactive material from the reactor or coolant system must be contained to mitigate offsite dose consequences. An LMFBR reactor containment, like a LWR reactor containment, is designed to accommodate, without exceeding design leak rates, the pressure and temperature conditions of Design Basis Accidents (DBAs). The CRBRP containment building shown in Figure 8 is surrounded by a confinement building. A negative pressure differential (-1/4 inch w.g. with respect to the atmosphere) is maintained in the annulus between the containment and confinement building to ensure that any potential leak would be into the annulus. All leakage into the annulus is filtered before being vented to the atmosphere. Thus, the containment/confinement structure provides a multiple barrier to a postulated release of radionuclides.

B. Use of Sodium as a Coolant

The advantages of sodium coolant thermal characteristics during a decay heat removal operation were briefly discussed in the last section. A key advantage of using sodium as a coolant is its high boiling point. As discussed in Section II.C, the large margin to boiling provided by sodium coolant allows LMFBRs to operate at atmospheric pressure. Thus, the potential for a sudden decrease in the saturation temperature due to rapid depressurization, a major concern in LWR safety, is not a concern in a LMFBR.

The primary disadvantage of using sodium as a coolant is its "chemical incompatibility" with water and air.

Although containment pressurization due to coolant flashing is not a concern for an LMFBR, a large sodium fire or similar chemical reaction can cause the containment to be pressurized. However, when inerted cells are used to minimize the effects of postulated pipe leaks, the largest credible sodium fire postulated to occur in the reactor containment building of an LMFBR would typically result in pressures much lower (on the order of one psig) than the pressures in an LWR containment following a major loss of coolant accident (normally in excess of several tens of psig). In addition, a sodium fire would occur on a much longer time scale (>50 hours) than the time for primary coolant blowdown following an LWR LOCA accident (on the order of several seconds).

Sodium/water reactions resulting from leaks in steam generator tubes are also safety concerns associated with LMFBRs. Considerable loadings could be applied to the IHTS and the intermediate heat exchanger following propagation of the sodium water reaction pressure front. Design features which preclude and/or mitigate the consequences of a sodium/water reaction in the steam generator system are included in the CRBRP design.

A steam/water to sodium leak detection system is provided to ensure that a sodium/water reaction could be detected and the necessary operator corrective actions taken, before extensive intermediate system and steam generator system damage could occur.

In addition, the CRBRP design includes a passive sodium/water reaction pressure relief subsystem (SWRPRS) that provides overpressure protection for the IHTS and IHX. The SWRPRS is illustrated in Figure 9.

C. Hypothetical Core Disruptive Accident

In an LWR the fuel, coolant, and structural material of the reactor core are arranged in a manner that maximizes K_{eff}. Any change in the core configuration due to fuel relocation or coolant loss tends to shut the reactor down neutronically.

An LMFBR reactor core, however, does not require a moderator, operates on a hardened neutron spectrum and is not in its most reactive configuration. Thus, if a fuel melting incident should occur, material motions could result in a net increase in reactivity.

Such an event is called a Hypothetical Core Disruptive Accident. HCDA progression may involve sodium boiling, cladding melting and fuel melting with relocation of the materials under gravitational and/or hydraulic forces.

The design approach for CRBRP is to exclude HCDAs from the DBA spectrum by providing features to prevent their initiation. The major features incorporated in the

CRBRP to prevent occurrence of HCDA initiating conditions include: 1) the redundant and diverse shutdown systems, 2) the redundant shutdown heat removal systems, 3) the means to prevent a double-ended rupture of the reactor vessel inlet pipe, and 4) the means to maintain individual subassembly heat generation and removal balance.

Even though HCDAs are beyond the design basis, features are included in the CRBRP design to provide additional margin for mitigation of these hypothetical accidents. Evaluation of HCDAs has shown that these features ensure that the residual risk is low.

Evaluation of HCDA energetics involves consideration of three accident phases: the initiating phase; a meltout phase which is entered if the damaged core is not stable and coolable at the end of the initiating phase; and a large-scale pool phase which may occur in the pessimistic case in which permanent subcriticality is not achieved in the earlier phases. A fourth accident phase, hydrodynamic disassembly, would occur if a sustained, super-prompt-critical excursion were to occur in any of the other three phases.

Realistic assessments of HCDA sequences, including best estimate analysis and consideration of uncertainties, have been performed and predict a non-energetic outcome (that is, there is no early mechanical challenge to primary system integrity). This is due primarily to the inherent dispersive nature of the fuel during the initiation phase of an HCDA. Fission gas and fuel vapor pressures provide a mechanism for enchanced fuel removal and thus, a greater potential for permanent subcriticality following initiation of an HCDA. Further analyses involving significant deviations from best-estimate understanding of accident physics have been performed. Pessimistic assumptions, well beyond those appropriate for a realistic assessment, must be invoked to predict energetics. The structural margin beyond the (SMBDB) design basis provided in CRBRP is adequate to contain the energetics predicted in these analysis.

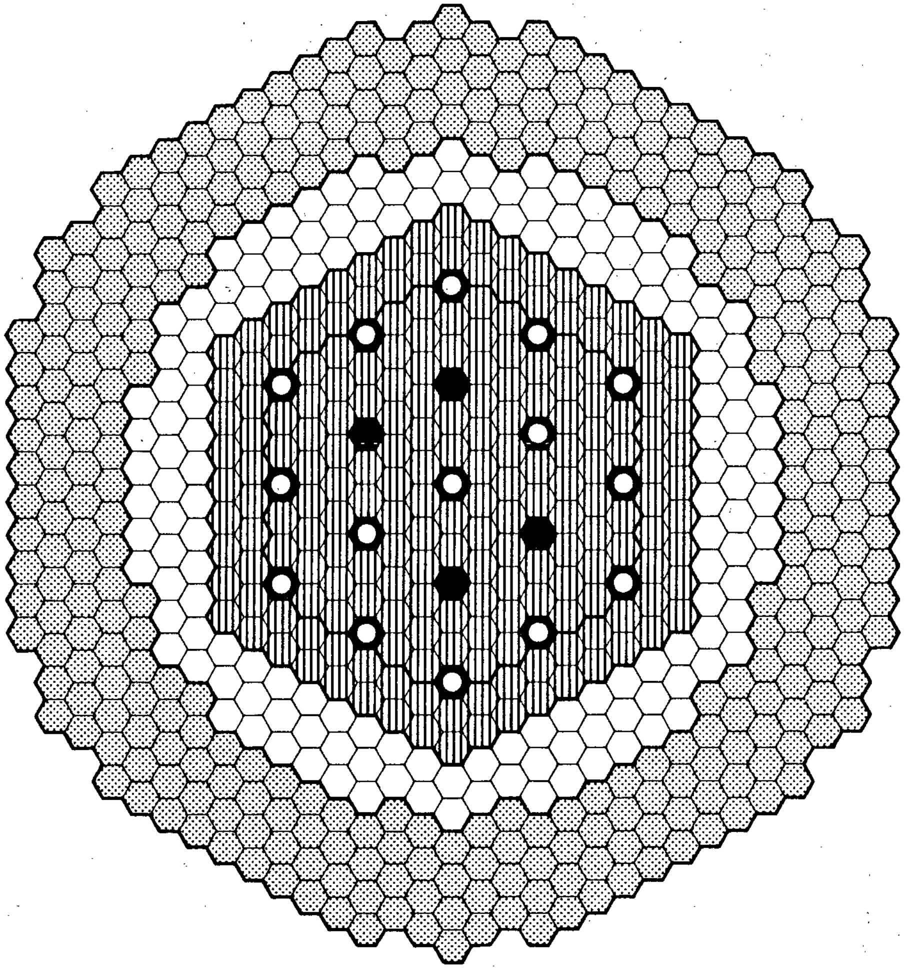
HCDAs that involve whole core melting could thermally challenge structures, including the reactor vessel and guard vessel. If the reactor vessel and guard vessel eventually fail, material would be released into the reactor cavity cell. The release of material into the reactor cavity could result in increasing pressure and temperature in containment from chemical reactions and heat input.

These potential thermal challenges from HCDAs are accommodated by designing to meet the Thermal Margin Beyond the Design Basis (TMBDB) Requirements. To meet the Thermal Margin Beyond the Design Base Requirements, design features have been added, including a vent between the reactor cavity cell and the containment, a system to vent and purge the containment through a cleanup system, a system to cool the containment vessel and the containment building, and containment instrumentation to permit the operator to follow the course of the accident.

Realistic assessments were performed considering sodium-concrete interactions, sodium-water reactions, decay heat, sodium burning, and hydrogen burning. These assessments show that the features provided would prevent uncontrolled release of radioactivity to the environment. These features maintain temperature, pressure, and hydrogen concentration in the Reactor Containment Building at acceptable levels in concert with the venting of the containment through cleanup systems. Best-estimate analyses show that the initiation of venting would not be required for more than a day after initiation of the HCDA. These analyses show that the radiological consequences of venting through the cleanup system would be acceptably low.

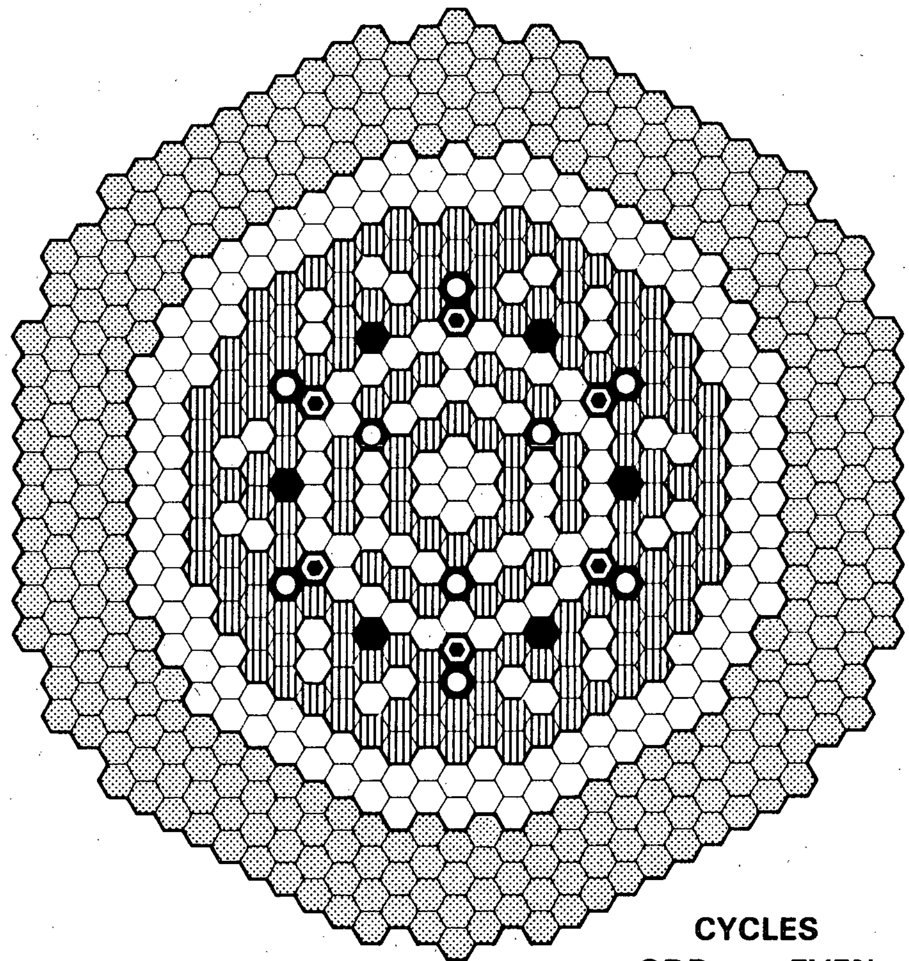
Sensitivity analyses have been performed relating the radiological consequences of HCDAs to the time of venting and show that the consequences would remain acceptably low for substantially earlier vent times than predicted in the best estimate analyses. Additional sensitivity analyses have shown that containment temperature and pressure margins would accommodate a wide range of material releases to containment in excess of those predicted from realistic assessment. Therefore, the design provides additional margins beyond those discussed in the preceding paragraphs.

CRBRP HOMOGENEOUS CORE DESIGN



FUEL	
INNER CORE	108
OUTER CORE	90
BLANKET	150
RADIAL SHIELD	324
PRIMARY CONTROL	15
SECONDARY CONTROL	4

CRBRP HETEROGENEOUS CORE DESIGN

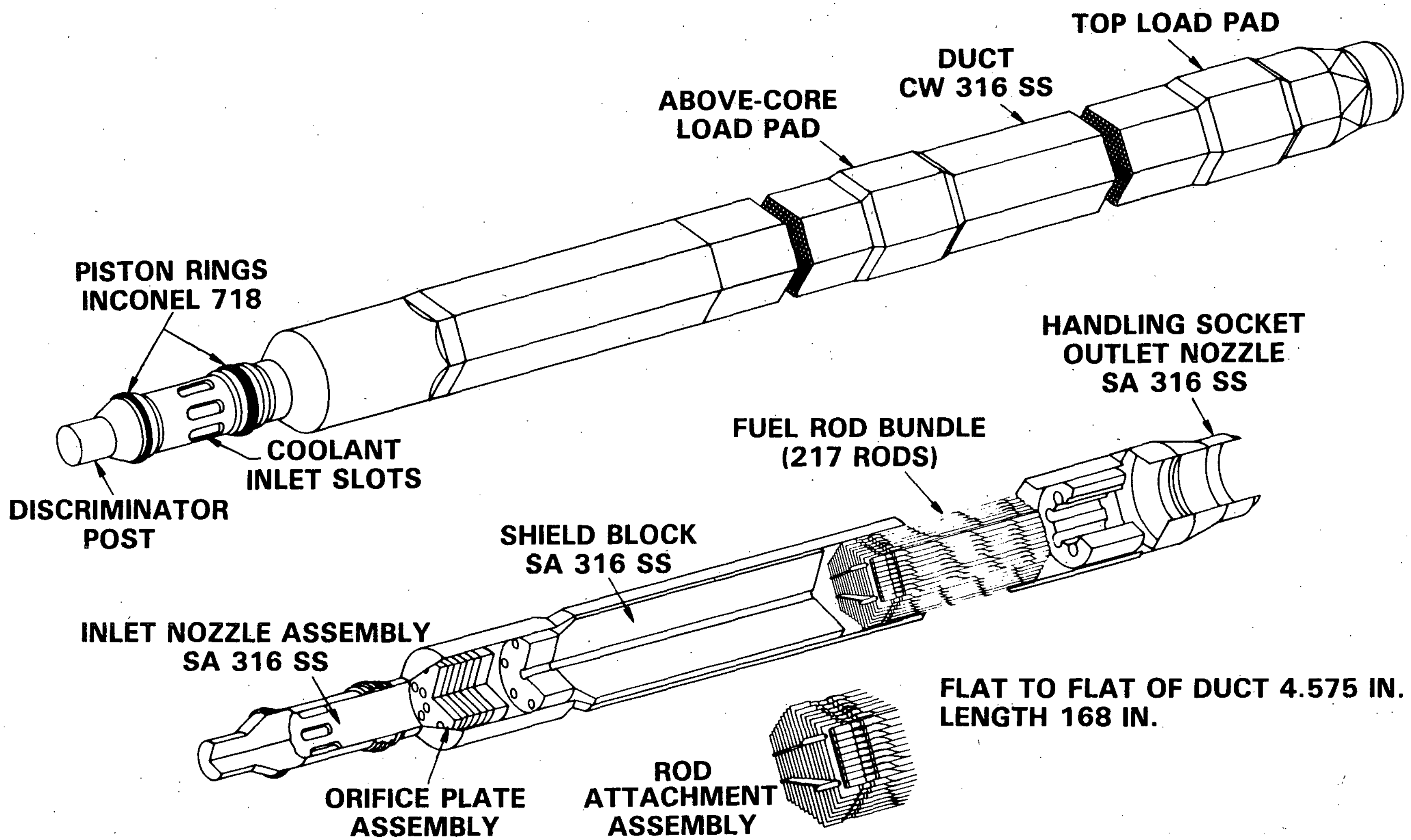


	CYCLES ODD	CYCLES EVEN
FUEL	156	162
BLANKET	208	202
RADIAL SHIELD	312	
PRIMARY CONTROL	9	
SECONDARY CONTROL	6	
ALTERNATE FUEL/BLANKET	6	

1-82-1296-18-8

Figure 1

CRBRP FUEL ASSEMBLY



FLAT TO FLAT OF DUCT 4.575 IN.
LENGTH 168 IN.

Figure 2

10-82-2573-2-1

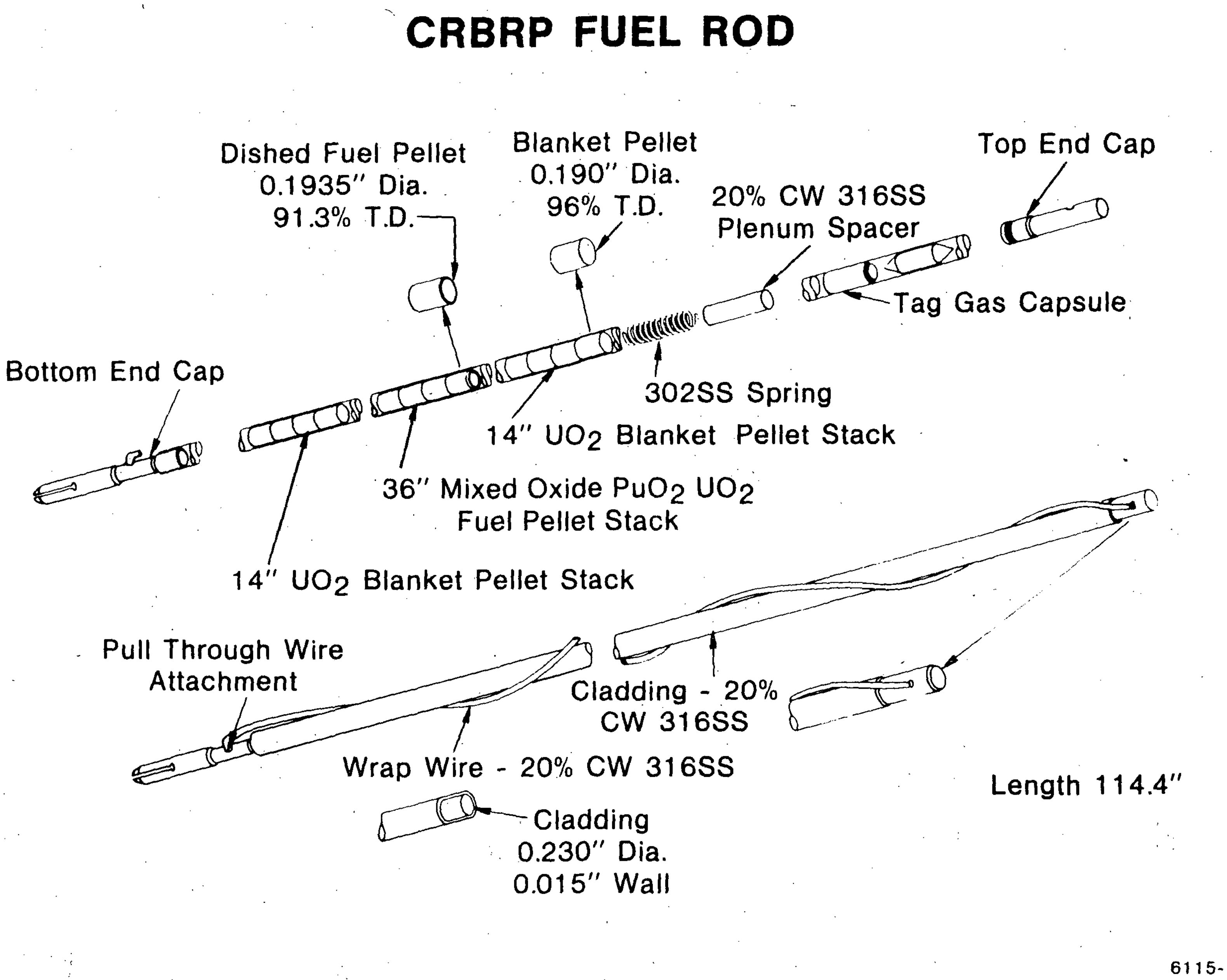

CRBRP FUEL ROD
Dished Fuel Pellet
0.1935" Dia.
91.3% T.D.
Blanket Pellet
0.190" Dia.
96% T.D.
20% CW 316SS
Plenum Spacer
Top End Cap
Tag Gas Capsule
Bottom End Cap
302SS Spring
14" UO2 Blanket Pellet Stack
36" Mixed Oxide PuO2 UO2
Fuel Pellet Stack
14" UO2 Blanket Pellet Stack
Pull Through Wire
Attachment
Cladding - 20%
CW 316SS
Wrap Wire - 20% CW 316SS
Length 114.4"
Cladding
0.230" Dia.
0.015" Wall
6115-1

Figure 3

CRBRP HEAT TRANSPORT AND POWER GENERATION

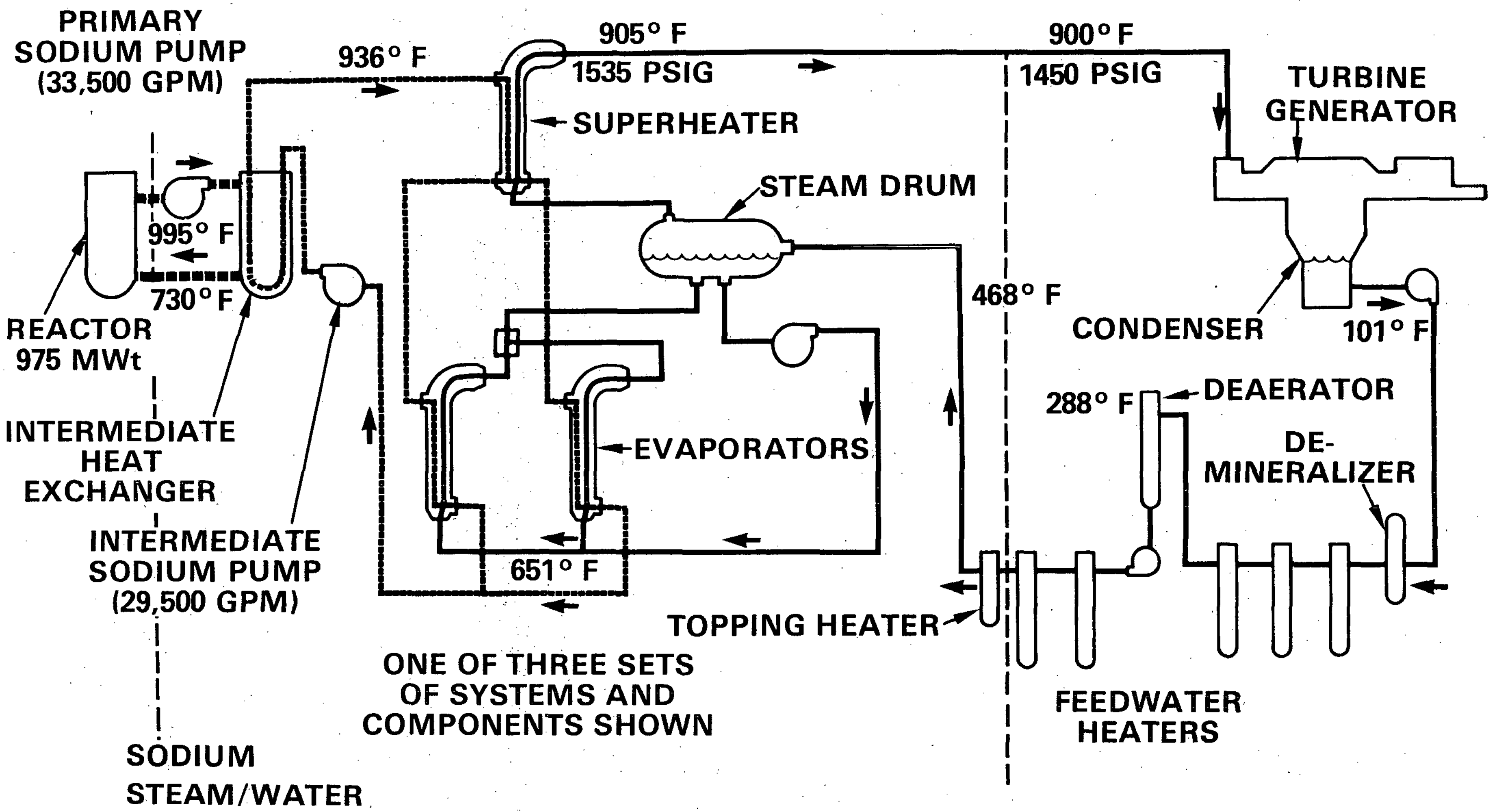


Figure 4

2-82-335-84-4

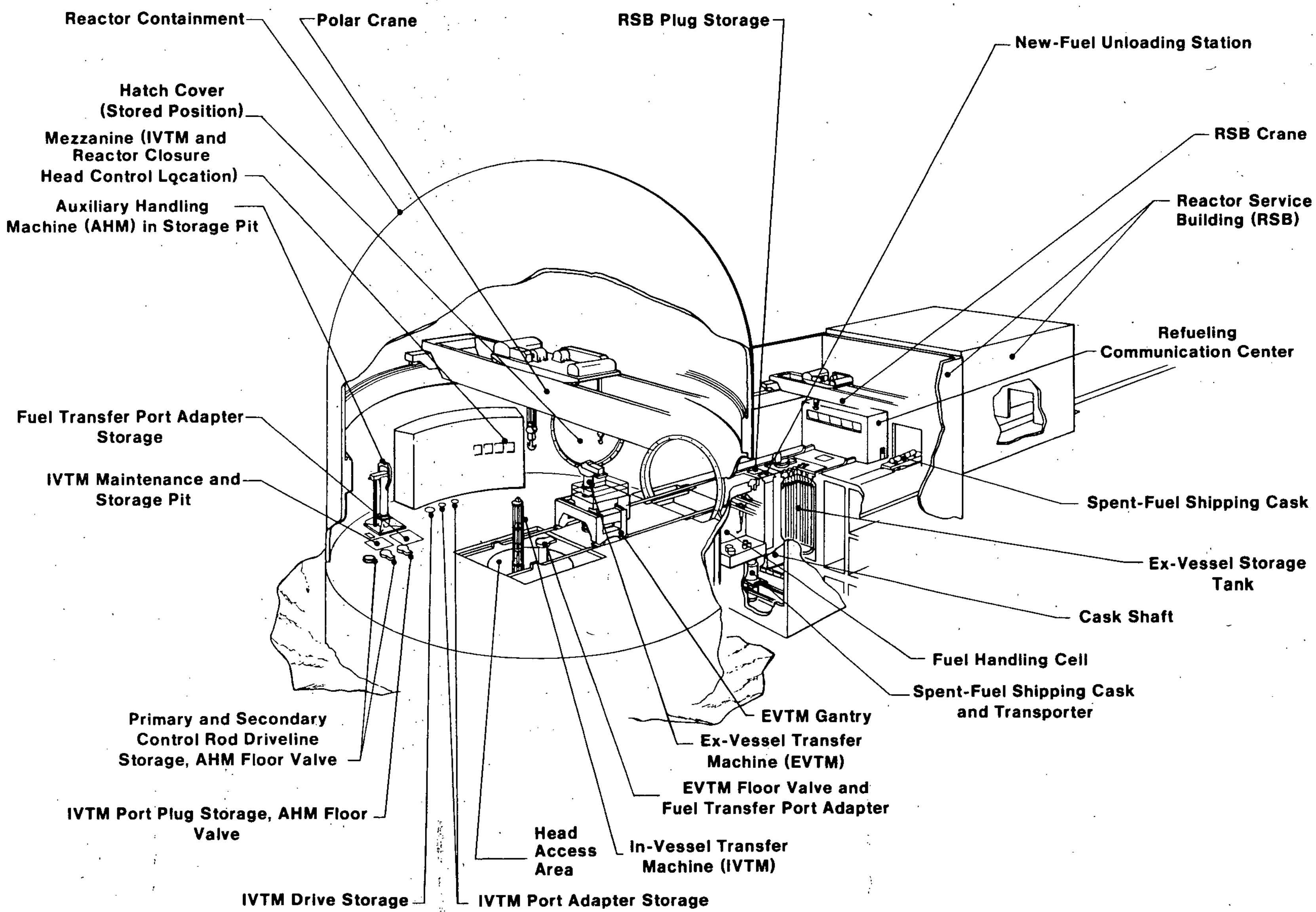

Reactor Containment
Polar Crane
RSB Plug Storage
New-Fuel Unloading Station
Hatch Cover
(Stored Position)
Mezzanine (IVTM and
Reactor Closure
Head Control Location)
Auxiliary Handling
Machine (AHM) in Storage Pit
RSB Crane
Reactor Service
Building (RSB)
Refueling
Communication Center
Fuel Transfer Port Adapter
Storage
IVTM Maintenance and
Storage Pit
Spent-Fuel Shipping Cask
Ex-Vessel Storage
Tank
Cask Shaft
Fuel Handling Cell
Spent-Fuel Shipping Cask
and Transporter
Primary and Secondary
Control Rod Driveline
Storage, AHM Floor Valve
EVTM Gantry
Ex-Vessel Transfer
Machine (EVTM)
EVTM Floor Valve and
Fuel Transfer Port Adapter
IVTM Port Plug Storage, AHM Floor
Valve
Head
Access
Area
In-Vessel Transfer
Machine (IVTM)
IVTM Drive Storage
IVTM Port Adapter Storage

Figure 5

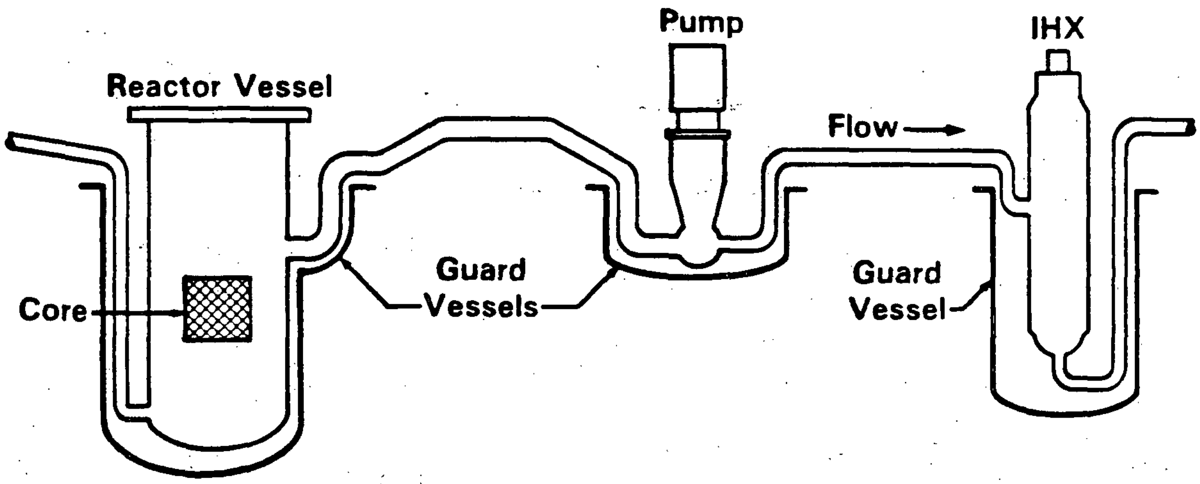
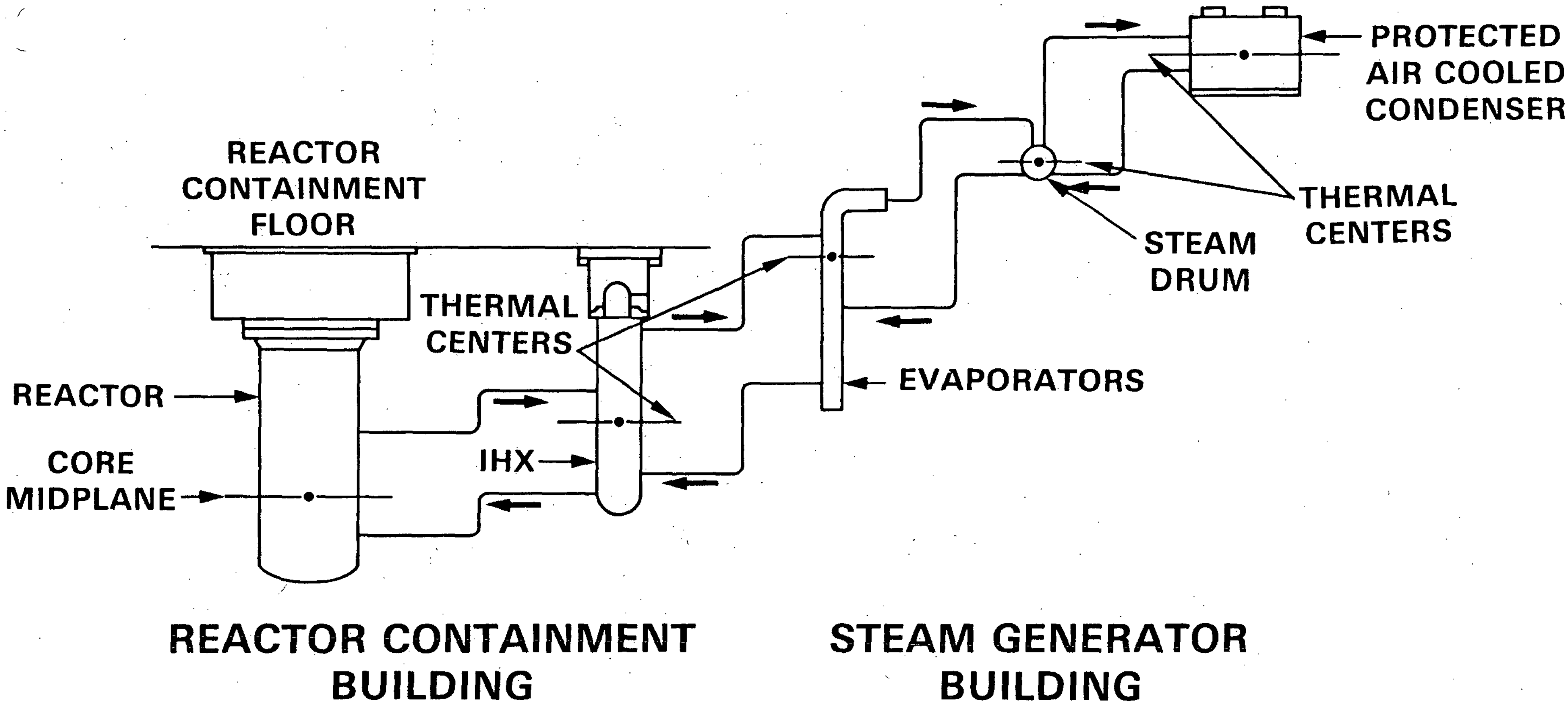

Pump
IHX
Reactor Vessel
Flow
Guard Vessels
Guard Vessel
Core

Figure 6

THE ELEVATION DIFFERENCES IN MAJOR COMPONENTS PROVIDE A NATURAL CIRCULATION CAPABILITY FOR CRBRP



10-81-2597-15

Figure 7